Density dependent spin polarisation in ultra low-disorder quantum wires

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There is controversy as to whether a one-dimensional (1D) electron gas can spin polarise in the absence of a magnetic field. Together with a simple model, we present conductance measurements on ultra low-disorder quantum wires supportive of a spin polarisation at $B = 0$. A spin energy gap is indicated by the presence of a feature in the range $0.5 - 0.7 \times 2e^2/h$ in conductance data. Importantly, it appears that the spin gap is not static but a function of the electron density. Data obtained using a bias spectroscopy technique are consistent with the spin gap widening further as the Fermi-level is increased.

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In the presence of strong exchange coupling, electrons can spin polarise in the absence of an applied magnetic field. Such a scenario is predicted for a variety of different systems including one dimensional (1D) ballistic quantum wires [1, 2], the two dimensional (2D) electron gas [3], three dimensional (3D) metal nanowires [4] and circular quantum dots [5]. In the case of 1D, interactions become increasingly important at low densities and models such as the Tomanaga-Luttinger liquid theory [6] are required to describe them. Despite the large exchange energy present in low-density 1D systems there are strict theoretical arguments against magnetic ordering [7] and the notion of a 1D spin-polarised ground state remains the subject of wide debate, in particular since the important experimental results of Thomas *et al.* [8]. Here we present experimental results taken on semiconductor quantum wires in zero magnetic field that provide strong evidence in favor of a spin energy gap developing in the 1D region. This density-dependent energy gap between spin-up and spin-down electrons is revealed in transport measurements as an anomalous conductance feature in the range $0.5 - 0.7 \times 2e^2/h$.

A feature near $0.7 \times 2e^2/h$ can be seen in some of the earliest 1D ballistic transport measurements on quantum point contacts [9, 10]. In 1996 Thomas *et al.* [8] revealed that the anomalous feature was related to spin by showing that it evolves smoothly into the Zeeman spin-split level at $0.5 \times 2e^2/h$ with an in-plane magnetic field. Since that time experimental studies have concentrated on the behavior of the anomaly as a function of temperature, source-drain bias, magnetic field, thermopower, wire length and density [11, 12, 13, 14, 15, 16, 17, 18]. Together with these investigations, numerous mechanisms to explain the origin of the conductance feature have been proposed [19, 20, 21, 22, 23, 24, 25]. Amongst the most compelling of these models is the notion of Fermi-level pinning in the presence of a static spin energy gap [24, 25].

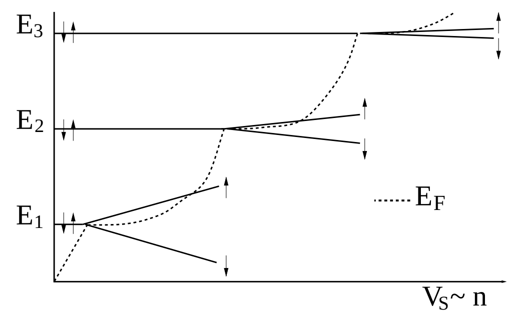

FIG. 1: Phenomenological picture of a density dependent spin gap opening linearly with increasing density (n) or gate voltage (V_S). E_1, E_2, E_3 indicate the 1D sub-band edges. The Fermi level (dashed line) is non-linear with density n due to the singularity in the 1D density of states.

In this work we propose, and present supportive experimental data for, an alternative simple phenomological model that appears to explain the characteristic details of the 0.7 feature by means of a *density dependent* spin gap arising in the region of the quantum wire. Key differences exist between this simple model and other explanations based on Fermi level pinning. As depicted in Fig.(1), the spin levels are degenerate when the sub-band is empty, with the spin gap opening up as the carrier density in the 1D sub-band is increased. Consequently this model also explains the absence of conductance plateaus at $0.25 \times 2e^2/h$ in the presence of a finite source - drain (S-D) bias.

In contrast to the case of a *static* spin polarisation, the sub-bands remain spin degenerate until they are populated, after which the spin gap opens with increasing density. This behavior, suggestive of many-body interactions, is consistent with a spin polarisation driven by exchange as predicted by Wang and Berggren [26]. In their calculations the polarisation weakens as higher sub-bands are populated (see Fig.1). The non-linear dependence of

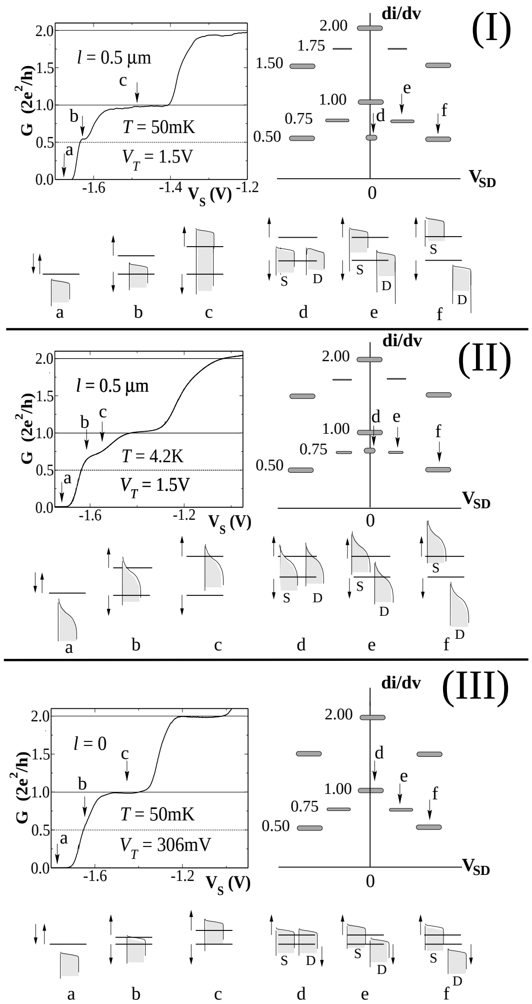

FIG. 2: Schematic showing the three main scenarios that lead to features near $0.5 \times 2e^2/h$ and $0.7 \times 2e^2/h$ in the conductance at both zero (left) and finite source - drain bias (right). In the lower portion of each graph the horizontal lines indicate the sub-band edges and shaded regions represent the Fermi distributions. Scenario (I) occurs if the spin gap is large in comparison to kT. Scenario (II) occurs at high temperature when kT is close to the size of the spin gap. Finally scenario (III) occurs for the case of weak spin splitting.

Fermi energy E_F on density or gate voltage in Fig.1 is a consequence of the singularity in the 1D density of states, $\rho \sim E^{-1/2}$ [23].

Our proposed model is consistent with conductance data we have obtained on GaAs/AlGaAs quantum wires free from the disorder associated with modulation doping [12]. Although we illustrate our simple model via comparison with this data, the model is not limited to these samples but appears to be consistent with the key published results [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18].

Turning now to the experimental data, we note that the presence and shape of conductance anomalies depend on the rate at which the spin gap opens with 1D density and are likely to be sample dependent. Figure 2 depicts the three main scenarios that may arise. Scenario (I) occurs if spin splitting takes place quickly with increasing density, so that an appreciable energy gap develops in comparison to the thermal energy kT. In this case we see a fully resolved spin-split plateau near $0.5 \times 2e^2/h$ in linear response conductance G and no feature near $0.7 \times 2e^2/h$. This is shown on the left of Figure 2(I), for a quantum wire of length $l = 0.5\mu m$ at $T = 50$mK. The right side of the figure shows the dependence of the differential conductance (di/dv) with finite source-drain bias, where the thick lines represent conductance plateaus. Due to an averaging of the conductance at the chemical potential of the source S and drain D, half-plateaus at 0.5 and 1.5 $\times 2e^2/h$ occur at finite bias when the two potentials differ by one sub-band [27, 28].

In a large applied magnetic field the Zeeman energy lifts the spin degeneracy, such that plateaus at $0.5, 1.5, 2.5 \cdots \times 2e^2/h$ are resolved in the the conductance [9]. The simultaneous application of a finite S - D bias then produces additional quarter plateaus at $0.25, 0.75, 1.25, 1.75 \cdots \times 2e^2/h$ [29]. However, in the case of a density dependent spin-gap at $B = 0$, the plateaus at 0.25 and $1.25 \times 2e^2/h$ will be absent, since the 1D electron density is not large enough to appreciably open the spin gap.

Scenario (II) considers the case where the thermal energy kT is comparable to the spin gap. In this case no feature near $0.5 \times 2e^2/h$ will be resolved as E_F crosses the band edges. Instead, as E_F approaches the upper spin band-edge, the spin-gap continues to open so that the number of electrons which thermally populate the upper spin band remains approximately constant. A quasi-plateau near $0.7 \times 2e^2/h$ therefore occurs due to the simultaneous increase of both E_F and the upper spin-split sub-band, (shown in the data for the same $l = 0.5\mu m$ wire at $T = 4.2$K). In this model the quasi-plateau can occur anywhere in the range $0.5 - 1.0 \times 2e^2/h$, as has been observed experimentally [14, 18].

The right side of Fig. 2(II) illustrates the behavior of the differential conductance at elevated temperatures. In contrast to the low temperature case of scenario (I), the feature remains close to $0.75 \times 2e^2/h$ even when the S - D bias is close to zero (Fig. 2(II) d & e).

Scenario (III) illustrates the case for where the spin-splitting is weak and only grows slowly with increasing density. At low temperatures a feature near $0.5 \times 2e^2/h$ is absent if the spin gap remains small in comparison to kT. We illustrate this scenario with data taken on a $l = 0$ quantum wire at $T = 50$mK. Although there is no evidence for a spin gap at zero S - D bias, the spin gap can still be observed as a feature at $0.75 \times 2e^2/h$ in the differential conductance as shown in the schematic on the right. This is because the splitting is too small to be resolved at low densities where $G < 2e^2/h$ at $V_{SD} = 0$. However, a moderate S - D bias evolves the $1.0 \times 2e^2/h$ plateau into a feature near $0.75 \times 2e^2/h$ as the source and drain potentials differ by one spin sub-band (Fig.

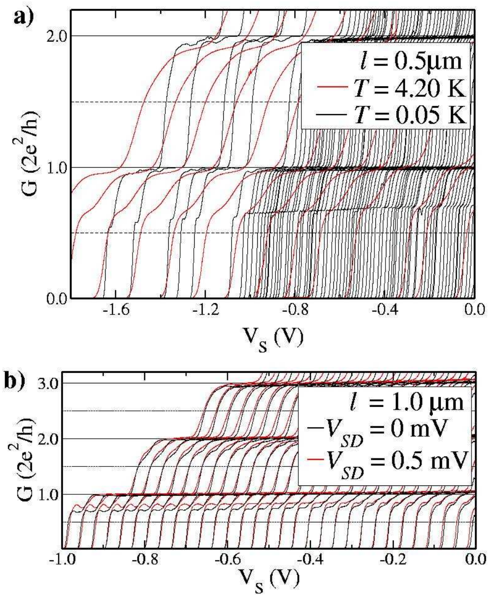

FIG. 3: **(a)** Conductance of a $l = 0.5\mu m$ quantum wire as a function of side gate voltage V_S for top gate voltages in the range; $V_T = 420$mV- 1104mV (right to left). **(b)** Conductance of a $l = 1.0\mu m$ quantum wire as a function of V_S for V_T in the range; 270mV - 800mV (right to left). T = 50mK.

2(II)e). Such behavior has been observed by Kristensen *et al.* [15, 30].

We now present conductance data taken on two different samples which support our model. The devices are fabricated from ultra low-disorder GaAs/AlGaAs heterostructures with electron mobilities in the range $4 - 6 \times 10^6 cm^2 V^{-1} s^{-1}$. Using electron beam lithography the top layer of the heterostructure is sectioned into three separately controllable gates with the middle or top gate being biased positively (V_T) to control both the density in the 2D reservoirs ($n_{2D} = 1.5 - 7.5 \times 10^{11}\text{cm}^{-2}$) and in the 1D channel [12]. The side gates are negatively biased (V_S) and simultaneously control the 1D density and the transverse potential. Careful control of all three independent gates allows the $0.7 \times 2e^2/h$ feature to be studied as a function of both density and potential profile. We find that the feature tends towards $0.5 \times 2e^2/h$ with *increasing* top gate bias and length of the 1D region [18].

Figure 3(a) shows data taken on a quantum wire of length $l = 0.5\mu m$ at T = 4.2K and T = 50mK. The data taken at T = 50mK show a characteristic evolution towards fully resolved spin-splitting with the 0.7 feature moving closer to $0.5 \times 2e^2/h$ with increasing top gate bias (right to left). In the context of the model this evolution is consistent with the spin gap opening more rapidly with 1D density n, for larger V_T, (i.e. moving from scenario III to scenario I with increasing V_T) although the exact mechanism behind the dependence on V_T is presently unknown [31]. In particular, the left-most traces from Fig.

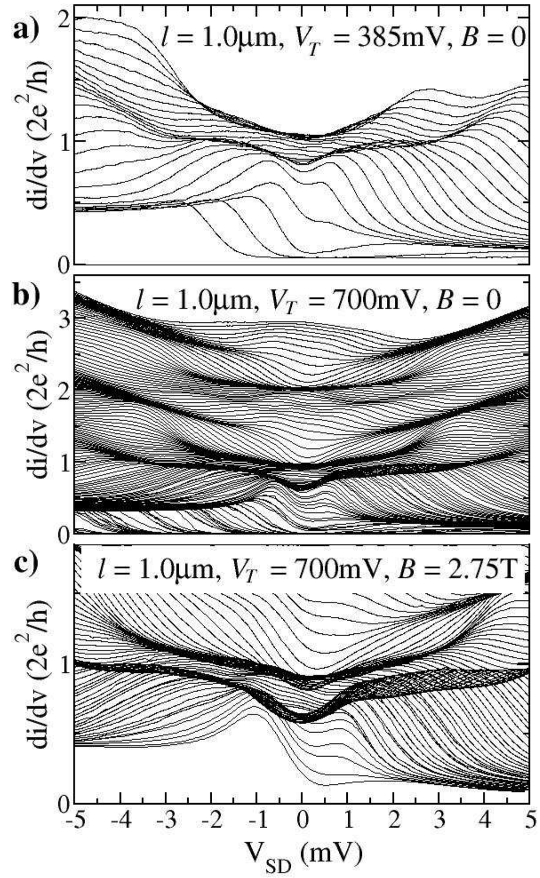

FIG. 4: Differential conductance of a $l = 1.0\mu m$ quantum wire. **(a)** V_S = 0 to -1200mV in -5mV steps. **(b)** V_S = -850mV to -1400mV in -0.5mV steps. **(c)** V_S = -900mV to -1400mV in -1mV steps. All data taken at T = 50mK.

3(a) are consistent with scenario (I) at T = 50mK and scenario (II) at T = 4.2K, where the feature has risen from 0.55 to $0.7 \times 2e^2/h$.

At T = 4.2K the position of the feature does not evolve with top gate bias (2D density) but remains close to $0.65 \times 2e^2/h$ at these higher temperatures, as both of the 1D spin bands are populated (*c.f.* Fig 2.(II)), and the position of the feature is rather insensitive to small changes in the spin-gap.

The shape of the feature will depend on the slope of the Fermi function as it crosses the second spin-band edge: at high temperatures the broad Fermi function produces a broad quasi-plateau. At low temperatures, depending on the size of the spin gap, the sharp Fermi function will either produce a small but sharp feature at $0.5 \times 2e^2/h$ (strong splitting, Scenario(I)) or a weak inflection (weak splitting, Scenario(II)) in the conductance.

Figure 3(b) explores the effect of a constant dc offset bias on both the shape and position of the conductance feature. At $V_{SD} = 0$ (black curves) we observe evolution of the feature from 0.75 towards $0.5 \times 2e^2/h$ with increasing V_T, consistent with the low temperature data for the $l = 0.5\mu m$ quantum wire shown in Fig.(3a) The

application of a DC offset bias $V_{SD} = 0.5$mV causes the feature to rise towards $0.75 \times 2e^2/h$, with a much weaker dependence on V_T. This behavior mirrors that in Fig 3(a) since increasing V_{SD} or increasing T will distribute electrons between both spin bands.

With the application of a dc source - drain bias the spin gap can be studied as a function 1D density, controlled by the side gate bias V_S. Figure 4 shows the differential conductance (di/dv) of a $l = 1\mu m$ quantum wire as a function of V_{SD} for different side gate voltages at $T = 50$mK. We compare the differential conductance at two different 2D densities ($V_T = 385$mV, $n_{2D} = 2.6 \times 10^{11} cm^{-2}$ in (a) and $V_T = 700$mV, $n_{2D} = 5.4 \times 10^{11} cm^{-2}$ in (b)). In these plots conductance plateaus appear as a grouping of individual curves, as can clearly be seen in Fig. 4(b) where plateaus occur at 2, 1 and $0.75 \times 2e^2/h$ for $V_{SD} = 0$. In both Figs. 4(a) and (b) clear half-plateaus at 0.5 & $1.5 \times 2e^2/h$ can be seen developing near $V_{SD} = \pm 1.5mV$, (although the 0.5 half-plateau on the right side of each graph is suppressed due to the asymmetric bias across the constriction near pinch-off [28]).

Most importantly there are no plateaus near 0.25 and $1.25 \times 2e^2/h$, despite the presence of strong features at $0.75 - 0.9 \times 2e^2/h$. This cannot be explained by a static spin gap, but is a natural consequence of a density dependent gap: at low 1D densities (small conductances) the spin gap has not yet developed, but at larger densities the gap opens up and features are observed at $\approx 0.75 \times 2e^2/h$.

Further evidence for the density dependence of the gap can be seen in the region close to zero bias where a characteristic 'cusp' feature is seen below the $1 \times 2e^2/h$ plateau. Traces associated with this feature start at $0.5 \times 2e^2/h$ at zero source - drain bias (scenario I) and move towards $0.75 \times 2e^2/h$ as V_{SD} is increased. As the 1D density is increased, (by altering V_S) the spin-gap widens, and a larger V_{SD} must be applied before the conductance increases above $\approx 0.5 \times 2e^2/h$. The cusp feature is a result of many of these traces overlapping, and the strength and width of the feature is a measure of how large the spin gap is, and how rapidly it changes with 1D density. The increasing strength of the spin splitting with increasing V_T can be seen in Figs. 4(a) and (b), where the cusp becomes deeper and more strongly resolved. With the application of an external parallel magnetic field the spin gap opens further and the cusp widens (Fig.4(c)) [32]. In future it may be possible to analyse the detailed shape of the cusp feature in order to obtain quantitative information about how the spin gap evolves with 1D density and parallel magnetic field.

In conclusion, we have presented a simple model to explain the $0.7 \times 2e^2/h$ conductance feature in terms of a density dependent spin polarisation arising in the 1D region. While our phenomenological model is consistent both with experimental data for ultra low-disorder quantum wires presented here, and with other published data, a detailed microscopic explanation of the spin polarisation is still lacking. In particular, the rate at which the spin-splitting grows with 1D density is sample dependent and seems to depend on the length of the 1D region, the surface gate geometry, and the 2D electron density. A detailed understanding of the spin polarisation will have implications for 1D electron transport in mesoscopic devices and may have important applications to the field of spintronics.

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[30] We note that the spin gap should remain constant with the application of a source - drain bias since, to a first approximation, the bias does not change the 1D density.
[31] Although the 2D density grows linearly with V_T, for a fixed conductance the 1D saddle potential (ω_x/ω_y) and the 1D density vary only a small amount as V_T is in-

creased.
[32] Unfortunately qualitative comparison is made difficult by the effect of the magnetic field on the ohmic contact resistance.